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Are Distributed Ledger Technologies the panacea for food traceability?

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A B S T R A C T

Distributed Ledger Technology (DLT), such as blockchain, has the potential to transform supply chains. It can provide a cryptographically secure and immutable record of transactions and associated metadata (origin, contracts, process steps, environmental variations, microbial records, etc.) linked across whole supply chains. The ability to trace food items within and along a supply chain is legally required by all actors within the chain. It is critical to food safety, underpins trust and global food trade. However, current food traceability systems are not linked between all actors within the supply chain. Key metadata on the age and process history of a food is rarely transferred when a product is bought and sold through multiple steps within the chain. Herein, we examine the potential of massively scalable DLT to securely link the entire food supply chain, from producer to end user. Under such a paradigm, should a food safety or quality issue ever arise, authorized end users could instantly and accurately trace the origin and history of any particular food item. This novel and unparalleled technology could help underpin trust for the safety of all food, a critical component of global food security. In this paper, we investigate the (i) data requirements to develop DLT technology across whole supply chains, (ii) key challenges and barriers to optimizing the complete system, and (iii) potential impacts on production efficiency, legal compliance, access to global food markets and the safety of food. Our conclusion is that while DLT has the potential to transform food systems, this can only be fully realized through the global development and agreement on suitable data standards and governance. In addition, key technical issues need to be resolved including challenges with DLT scalability, privacy and data architectures.

1. Background

Providing consumers with safe food of the nature and substance both intended and expected, is a key and legally defined requirement for all food businesses. All food businesses manage safety by deploying traceability systems (see recent reviews of Elliott, 2014; Badia-Melis et al., 2015; Olsen and Borit, 2018). Despite these systems, food fraud, adulteration/contamination and food poisoning still have significant societal impacts (see e.g. Manning and Soon, 2014). The immense scale, speed and complexity of global food supply chains now create significant opportunities for the production and rapid distribution of adulterated or unsafe food (Ercsey-Ravasz et al., 2012). Food contamination is the root cause of approximately 420,000 deaths each year (World Health Organization, 2015), food fraud and adulteration costs are difficult to estimate but could be > $40bn (PWC, 2016). The economic impacts of supply chain failures are significant, for example, Moyer et al. (2017) considered that the cost of the EU 2013 horse meat adulteration issue (see O'mahony, 2013) was "*incalculable*". Globally, the need to reduce food borne disease is recognised in the UN Sustainable Development Goals (Goal 2. End hunger, achieve food security) and the World Health Organisation (World Health Organization, 2015) states that: "achieving food security and ensuring healthy lives, will depend in part on successful reduction of the burden of foodborne diseases".

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2. The importance of traceability in food safety

Effective traceability systems that minimize risk are recognised as a critical tool to assure food safety (Aung and Chang, 2014). International food traceability standards are set through the joint FAO and WHO Food Standards Programme – the Codex Alimentarius Commission. The principles of food traceability are laid out in CAC/GL 60–2006: “The traceability/product tracing tool should be able to identify at any specified stage of the food chain (from production to distribution) from where the food came (one step back) and to where the food went (one step forward), as appropriate to the objectives of the food inspection and certification system” (CAC, 2006). The adoption of these principles is underpinned by national and international regulation (see e.g. EU Regulation (EC) No 178/2002, and national approaches reviewed by Charlebois et al., 2014). This pragmatic one up/one down arrangement connects all bound supply chain members as all actors know who their suppliers are and where their product is sold. However, reliance on the one up/one down approach still leaves the supply chain vulnerable, as many food products have complex multi-step vertical and horizontal branching supply chains (e.g. multiple ingredient products). In addition, one up/one down traceability can be easily lost in commodity products that are blended (e.g. milk from multiple farms in a dairy) or dissected and mixed through the supply chain (e.g. animals for meat production). With such complexity, it soon becomes impossible to verify the provenance and quality standards of specific products. In addition, the food industry is still largely reliant on paper records, with limited amounts of these ever being captured into a computerized and searchable format. Poor transparency through multiple supply chain steps can promote or conceal fraud.

3. Distributed Ledger Technology and blockchain

Distributed Ledger Technologies (DLT, Walport, 2015; Maull et al., 2017), such as the various implementations that also comprise Blockchain, where data resides on ledgers (a log of transactions) but cryptographically connected in chains of blocks, is proposed as an additional solution to the above challenges, allowing regulators, consumers and businesses potentially to instantly access the whole supply chain of any food and drink.

Ledgers are replicated (distributed), with identical copies held by all system users. New data is only added to a ledger by consensus, when all users agree the data is accurate. Any attempt to alter data by a single user will be transparent to all users, in theory, creating immutability. Early prototype systems are starting to emerge for dedicated application within the food supply chain (e.g. Tian, 2016, 2017; IBM Food Trust, 2018, Mao et al., 2018). In addition, twelve of the biggest global food companies have been adopting the use of blockchain to support how industry tracks food in the world; examples of these companies are Walmart, Nestle, Unilever, Tyson Food, Driscoll's, and Dole Food (Forbes, 2018).

Fig. 1 illustrates the application across a whole food supply chain from farm through to cooking by the consumer. Each member of the chain (farmers, food manufacturers, hauliers, retailers and consumers) may have access to a full copy of the ledger, data is sent to the ledger by all supply chain actors, but is only accessible to others by permission. The data is gathered in coherent “blocks” that are connected together with immutable encrypted keys. With permission any actor in the chain can see the complete provenance of a food item as it moves up and down the supply chain, as well associated metadata (temperatures etc). In addition, regulators would have a “read only” access to the ledgers giving them instant access to the complete provenance of any particular food item, across multiple international actors. The data connectivity, speed of access and its immutability provides, in theory, a step change in food traceability, even enabling regulators to instantly unravel multi component products (e.g. in Fig. 1 where animal protein is mixed with grain based products).

Technically, blockchain is a distributed database that records peer-to-peer electronic transactions permanently, so that transactions can only be accessed, inspected and updated. Blockchain uses cryptographically secure keys to link all transactional elements of a supply chain, putting trust directly in the network and avoiding the need of central trust institutions. The trust in a blockchain is applied to data, services, processes, identities, business logic, or any digitalised asset. More specifically, a blockchain is a place in which data can be linearly stored semipublicly in a container (in a block). Anyone can verify that the data has been placed in a container, but only the ‘owner’ of the data (the one who added the data) can unlock the content of a container by using private keys.

The chain of keys resides in ledgers that, providing they are widely distributed (cf. Distributed Ledger Technology - DLT), prevent any malevolent actor from defrauding or manipulating data. Any person or company participating in a DLT system has access to their own replicated copy of the ledger, new copies of the ledger are only available when sufficient numbers of actors within the system agree that the data in the ledger is correct (consensus). Ledgers are modified and built upon only by the consensus of all actors in the chain, and any attempt to manipulate ledgers at any point would be seen, in theory, across all members of the chain. The consensus mechanism and transparency underpin trust. The chain can also contain encrypted keys to additional metadata (e.g., temperature, provenance data, etc.) that sit on or off the ledger, but which has been collected to further document food safety. Encrypted keys provide proof of data adulteration: any digital data set generates a unique key, when tested the same data set will always generate the same matching key as long as it has not been adulterated. Adulterated data may provide evidence of adulterated food. In addition, smart contracts can reside on the ledger, including machine executable contracts. For example, the ledger could contain reconciliations of how a batch of food has depleted through manufacturing. This can evidence non-adulteration, since any batch should deplete to zero during production of next stage food items and cannot have a greater mass than

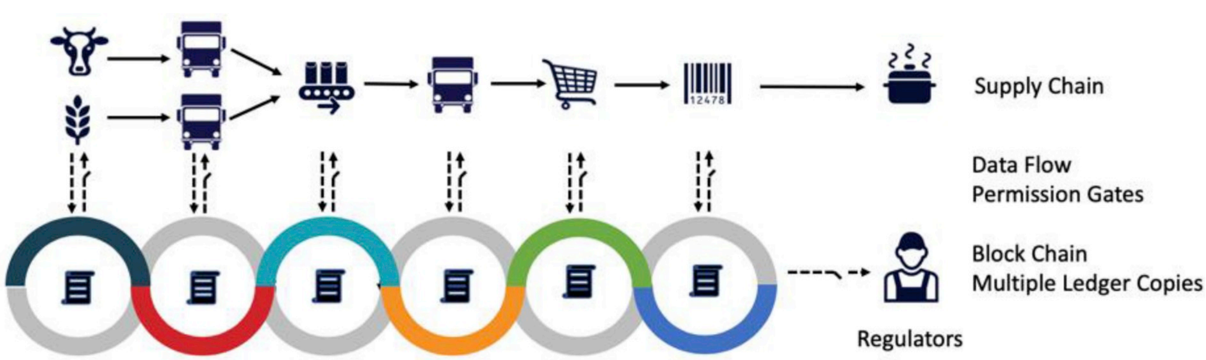

Fig. 1. A schematic diagram demonstrating the flow of data within a food supply chain connected by distributed ledger technology.

the incoming component mass minus losses and waste.

The immutability of a securely linked blockchain could in theory be a *panacea* for food traceability record keeping that could either evidence adulteration at any stage of the production and distribution pipeline or accelerate high fidelity tracing and resolution of food safety issues. Effectively all records required for food traceability are kept as replicated digital records of linked transactions across whole supply chains. While it could not prevent malign actors from changing batches prior to or after data being recorded on the blockchain, or the use of incorrect data, it would still provide a powerful deterrent to more traditional fraud mechanisms. The DLT deterrent to food crime is that the records are in theory immutable and open to all actors, with permission, to the ledger. All actors within a global supply chain can identify and report malign actors and immutable records provides a safer basis for public prosecution or private sanction. DLT therefore helps secure the evidence chain, it does not replace any of the industry and regulatory standard procedures (e.g. audit, risk management, food forensic investigation) required and widely adopted to control fraud and adulteration (see Elliott, 2014; Manning and Soon, 2014). It prevents malign actors from concealing their actions by changing records.

However, the consensus process, whereby actors verify the quality of each other's data prior to accepting it within a block, develops a higher degree of supply chain trust. Malevolent actors could be rapidly exposed and sanctioned in a more open supply chain ecosystem. The management of sanctions should, in our view, require careful governance. There is a real risk that innocent parties might be incorrectly sanctioned by other actors in the supply chain, or disproportionate penalties might be applied to defaulters. Unsubstantiated allegations can easily arise in high speed and volume market places, where quality standards can be subjective. In these instances, clear public and private governance rules and processes, that include guidance on confidentiality and data ownership, are required; an ultimate sanction might be to exclude a supplier from the DLT (and therefore their product from the food chain), though all entities have a clear legal right to their own defence.

Blockchain and DLT should accelerate the tracking and tracing of biologically variable food across complete, even global, supply chains, thus markedly improving the management of quality issues and serious breaches in safety (food poisoning, adulteration, contamination). Rapid and high fidelity tracking and tracing of whole food across supply chains (beyond one up/one down) will provide the most significant global impact of DLT; when food safety issues occur, societal impact is reduced by rapid and co-ordinated action to contain risk. DLT enables both high speeds backward (to verify provenance of products within a batch) as well as forward traceability (to verify where a high risk or faulty product may have been used elsewhere within the supply chain). Like all traceability systems it is pragmatically limited by process steps within the food chain (e.g. product mixing to make blends, batch disaggregation), but even with blended or disaggregated products high speed tracking, plus ready access to metadata, creates time for operators to isolate and manage risk.

An alternative method to DLT that links global food traceability would have all actors depositing their information on a single, or few, regulated ledgers. This ledger could in theory connect supply chain links in secure blocks (aka blockchain, but with a single ledger). However, this single trusted party does not exist in the food chain and, even if it could be envisaged and we do not discount it, it would have to be as global as the supply chain – this seems highly unlikely to be achieved in the current market.

4. Permission

It is clear that speed of detection and reaction is critical to the management of safety issues in the food supply chain. The current "one up/one down" legislative standard is slow, requiring multiple actors in unison to track products through their individual safety systems. While food regulators have the power to compel all actors within a supply chain to report the provenance and safety assessments of any food as it flows through the supply chain, such requests for information are only made in exceptional circumstances and in the interests of public safety. Private companies do not have the same power as food regulators: their access to confidential data can only be granted by the consent of all other actors in the chain, and in a step-by-step backward process down and across the whole chain. On this basis, only a "permissioned" blockchain architecture (see Swanson, 2015) such as that enabled in the Hyperledger fabric (Hyperledger, 2018) or the BigChainDB system proposed by Tian (2017) could be suitable for complex global food supply chains, whereby access to data along the chain can only be granted by permission of the data owners. Private companies are obligated to keep key data confidential. They could in-advertently breech anti-competitive trading regulations if they reveal confidential information of trading activity to and between competitors. It is clear, therefore, that international standards and guidelines are required to agree what data is stored on a food blockchain register, the consensus mechanism, confidentiality and how other people have access to it. These standards should also define how the data is owned, used and stored, and by whom, within the chain. For example, it is in the public interest for regulators to "mine" whole supply chain data for food safety surveillance and monitoring, but unless food specific "data access standards" are developed, privacy provisions would in effect limit the potential of DLT for private companies to little more than what they can already achieve without blockchain technology. Data access standards are needed to define what data (e.g. provenance, not price) can be obtained by - and by consent from - any actors within a supply chain. Global blockchain standards for all industries are now being developed by the ISO Blockchain (TC 307) initiative. However, these are not industry specific and food standards need to be developed as an addition to this ongoing international process.

5. Could "blockchains" block access to markets?

While blockchains can document and connect complex global supply chains, the IT infrastructure required to operate and maintain the system might prevent access to markets for new users or food suppliers. The systems could, in effect, become a technical barrier to trade, thus reducing market competition and access (i.e., those that are not in the chain cannot participate). It would be unacceptable if "blockchain" effectively blocks and constrains access to the global food supply chain. This is a tangible issue for any smaller producers in both developed and developing countries who may wish to export product into global markets. Conversely resolution of these technical barriers provides an opportunity for new entrants, since food trust is enhanced. It is critical that access to blockchain technology be kept simple, low cost, and easy to implement and deploy. This requires global standards for data encryption, DLT architectures and access. Agreed standards are needed to enable the sharing of data across digital platforms and within supply chains. Developers are clearly aware of this issue and the Linux Foundation Hyperledger fabric, which uses open source blockchain has a strong focus on simple API (Application Programming Interface) development. However, the creation of international standards is cumbersome and requires considerable commitment from all sectors in the chain.

6. Scalability

Blockchain technology is best known as the system that underpins BITCOIN and other cryptocurrencies. It is well known that BITCOIN platform maintenance, in particular mining, requires a huge amount of computational resource and is estimated to consume up to 43.9 MT of CO_2 per annum (Foteinis, 2018), equivalent to that consumed by 6.8 M European citizens. These challenges demonstrate potential scalability issues in large supply chains. Blockchain applied to the food system will not require the mining associated with BITCOIN, but the data scale could be significant. The global food supply chain is vast, not only involving primary producers (the Food and Agriculture Organisation FAO) estimates that there are about 570 M farmers globally), but also involving their suppliers, logistics companies, food manufacturers, retailers, restaurants, and consumers. In addition, many food products comprise multiple ingredients, generate huge amounts of metadata (e.g. cooking and refrigeration temperatures), and require support from secondary supply chain providers (e.g. refrigeration companies, audit and assurance companies, food processing equipment, labelling companies, etc). By crude comparison with global individual data platforms such as Facebook and similar, we estimate data in the food supply (block)chain could eventually reach Petabyte scale per year. The data scale is a function of the number of system users (nodes), since each node would have its own replicated copy of a ledger that could link thousands of transactions.

In order to illustrate the data scale, consider each person in the UK (68 m people) completing and recording in DLT the consumption of 5 pieces of food each day. Assume that data is stored in a block restricted to 1 MB of new information (256 bytes per transaction), and that the chain renews and adds a new block every 10 min (aka the Bitcoin block generation rate). In this case, 85 GB of data will be generated per day and 31 TB of data will be generated over a year. If we expand the chain to include 5 prior steps (i.e., farmer, farm logistics, food manufacturer, logistics and retailer), but assume a compression ratio (as food moves down the supply chain in large batches and not as individual items) of 1000 per unit of food sold in the retail chain, again with no metadata attached, the supply chain ledger would generate an additional 155 GB of data per year.

This theoretically large ledger would need to be refreshed, transmitted or cloud replicated globally to all DLT nodes in the system every 10 min (as each block is generated). Clearly, these data calculations are highly speculative, but do indicate the potential scale challenge in applying blockchain to the food industry. We see this as a key technical challenge. Moreover, different architectures are emerging that attempt to resolve this issue (Tian, 2017; IBM Food Trust) but clearly multiple standards need to be interoperable otherwise they become a barrier to trade. This analysis emphasizes the need for more research on optimizing the scalability whilst maintaining interoperability of blockchain architectures for food. A recent review cited a lack of scalability research as a concern for the whole of blockchain technology per se (Yli-Huumo et al., 2016). Our analysis emphasizes the need to prepare for significant data scale.

Given this complexity, it is likely that blockchain solutions will first emerge in niche, controlled or high-risk areas of the supply chain, where the technology may have the most significant impact. An example of a controlled supply chain might be where a retailer with significant scale requires suppliers to use a dedicated DLT system for food traceability. The governance of this controlled chain is led by a consortium including the retailer, suppliers and IT/DLT provider. It is quite likely that this approach will create an initial stimulus to use blockchain in global food chains. Whilst this may provide a competitive advantage for the controlled chain members, there is a risk/likelihood that different retailers will adopt different standards resulting in a number of multiple inoperable DLT silos emerging. This would increase supplier costs (maintaining multiple ledgers), constrain regulator ability to operate and potentially become a barrier to trade.

Technical barriers to trade are significant in the context of global food security. It would be unacceptable to deny farmers, or any supply chain actor, in both developed and developing countries access to a supply chain based on the need for specific and perhaps complex digital infrastructure. Overcoming these challenges, by enabling access to DLT via low cost hardware (smartphones/tablets) and software independent of farm size and suitable for all farmers and small holders, is essential. Pragmatic, low cost and accessible DLT that enhances supply chain trust and trust worthiness will enable trade. This is because all actors within a chain can rapidly establish provenance and view linked metadata that includes accurate records of food origin and quality (e.g. temperature, quality, audit and product age data). DLT could catalyse and potentially disrupt global food trade and access. Improved trust and transparency democratise, widen access, simplify, reduces cost (e.g. need for third party audits, lower waste, fewer supply chain links etc), increases supply chain efficiency and protect consumers. In theory consumers can view the provenance of their food back down a supply chain (so they self-select product based on experience), whilst farmers could view the route their product has taken up to the consumer. Self-selection and repeat purchase by consumers of specific farmers product enabled by increased transparency rewards producers on the basis of performance. This transparency increases equity through the supply chain since there is a clearer and more open understanding of how value is added through a products life cycle.

It is clear that the food sector will need to rapidly consider how to adopt DLT across the supply chain. Ultimately application will be a consequence of a pragmatic approach to data scale balanced against both risk and trust. If controlled chains (e.g. retailer led) exist with high levels of trust, for example embedded by long term trading relationships in a highly regulated environment (e.g. abattoirs), then a DLT structure with relatively low numbers of ledger copies (nodes) and simple consensus rules would be appropriate. However, in chains with more limited prior relationships or fewer audit and regulatory controls then wider ledger distribution (high numbers of nodes), with more robust consensus arrangements and cryptography might be necessary.

7. For how long do we need to keep the data?

In the EU legislation, there is no set time or legal minimum for how long food safety, quality and legal records must be kept. Different countries may even take different approaches. However, it is important to consider the length of time over which a food might be consumed, i.e. the durability date (typically a “Use-By” or “Best Before” date), and also the need to provide information should a related complaint be raised at any later stage. In the UK for example, best practice laid down in the Food Industry Guide to Good Hygiene Practice Wholesale Distribution (Food Standards Agency, 2007), recommends that product records are kept for a minimum of three years. Even more conservatively, many retailers look to keep their records for up to seven years from sale. At present, there is no obvious economic - or legal - value in retaining records for periods greater than any likely statutory period, added to which the cost of doing so may become burdensome to businesses. However, and in theory, blockchain systems by themselves can provide immutable and permanent records. The challenge in recovering data will then be mainly associated with possible changes in trading relationships between partners. For example, in a permissioned ledger, a supplier may not be willing to open their chain to a customer or the supplier may cease trading with the buyer. Changes in business relationships may, therefore, break the “permanent” digital chain. To overcome these issues at regulation level, a system may be required that provides a “golden key” for regulators to recover information from the chain regardless of whether the initial permissions are still considered in effect or not. In addition, it is highly likely that more proprietary metadata (cooking temperatures, microbiological results, etc.) will be held off the chain and coded by encrypted keys to show that it has not been altered. Due to technical obsolescence (e.g. of the support, communication or coding mechanism), it is quite likely that such links will cease to be available over time, and data standards are, therefore, required to ensure that data is correctly archived and remains available for agreed durations post-marketing of any food item.

8. Who would/should/could Own(s) the food blockchain?

The data platform necessary for a food industry blockchain will require major investment in substantial IT developments and infrastructure, which includes API's to encrypt and recover data, ledger creation and maintenance, storage and communications, etc. Ideally, the ledgers should automatically generate blocks through the manufacturing process and be linked to standard Enterprise Resource Planning (ERP) systems. The challenge will be to decide who governs (Kewell et al., 2017) and how to pay for this IT infrastructure. In this case, there are opportunities for innovative IT systems and business models to emerge.

9. Final remarks

We believe that DLT in general, and blockchain in particular, can be used as a technology to assist with food traceability, the ability of DLT to rapidly trace food beyond one up/one down is critical and novel but it is not a stand-alone panacea. Despite its benefits there are still several open challenges that need to be addressed before DLT can be used to support food traceability. Examples of these open challenges are concerned with the need of data standardization in the food domain, ease of use to remove barriers to entry to the food supply chain, governance mechanisms, enhancement of the technology to cope with a large amount of data (scalability), privacy mechanisms to protect users and an iterative approach is required to underpin the adoption of the technology across the whole chain. Our expectation is that blockchain implementation will be primarily driven to improve speed and fidelity of traceability to protect brands (private action) and the public (regulator action) from food safety issues.

Declarations of interest

None.

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Appendix A. Supplementary data

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